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A PRACTICAL METHOD FOR DETERMINING THE DIRECTIVITY OF H. F. AND V. H. F. ANTENNA SYSTEMS

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1. INTRODUCTION.

Whenever radio or radar systems are an integral part of a scientific experiment, it is essential that the radiation characteristics of the antennas employed should be accurately known in order to interpret the experimental results properly. Also, economic considerations usually dictate that the antenna be designed to produce a radiation pattern which allows most efficient use of the available power. The only conclusive way of checking whether these requirements are met is by measuring, in situ, the actual antenna performance. Such measurements, in which the antenna and its surroundings are considered as an integrated radiating system, not only provide a check on the antenna design but also indicate whether there is any need for adjustments.

In the past, H.F. and V.H.F. antenna measurements have been made either on the actual full-sized system by using aircraft or on a scale model of the antenna and its surroundings. The techniques in current use are classified and described in a survey paper by Cumming (1959).

The use of aircraft is expensive and demands accurate knowledge of the aircraft's position as a function of time. If the airborne test antenna is mounted on the aircraft, interaction between it and the aircraft severely complicates its radiation pattern in a manner that is not easily allowed for. This complication may be minimised by towing the test antenna on a stabilised drogue at the end of a long cable (Brueckmann, 1955). If, however, the position of the test antenna is determined from the position of the aircraft, by radar fixes for example, allowance must be made for the drogue drifting in the wind. Furthermore, if the flight is made in a straight line at constant height, as is often the case, the receiver and measuring equipment must be capable of handling wide variations in signal strength, especially when highly directional antenna systems are being measured. Generally speaking aircraft techniques are best when the design frequency of the antenna is under 20 Mc.

The use of scaled models involves close tolerances in dimensions as well as in the conductivity of the ground plane. If the scaling factor is large this method may prove to be impractical, especially for Yagi antennas which are by their nature very dependent on the self-reactance of the various elements, and hence on the element diameters (Cumming, 1959). Reproducing to the correct scale the surroundings of the antenna at its final site often rules out the use of scaled models; in situ measurements being the only alternative.

In a recent paper Brueckmann (1963) has shown how radio transmissions from a satellite were utilized for determining the radiation pattern of a large multiple-beam array and advocates the launching of an antenna calibration satellite. This approach may have advantages for calibrating certain antenna systems but lacks the flexibility needed to cope with a wide variety of antenna designs and frequencies.

This report discusses the merits of a hitherto unpublished, inexpensive technique, whereby a small self-contained transmitter and dipole antenna is suspended from a meteorological balloon flown at constant distance from the centre of the antenna array to be measured. The variation in signal strength indicated by a receiver connected to the array gives a direct measure of the radiation pattern as the position of the balloon is varied. By the Reciprocity Theorem the radiation pattern of an antenna is the same whether it be transmitting or receiving, provided non-linearities are absent. Thus radiation pattern measurements may be carried out equally well by probing the transmitted field of the antenna or by measuring the angular variation of the antenna's response to an incident wave. The latter approach was adopted in this case simply because it is much easier to construct a lightweight transmitter than lightweight receiving and recording equipment.

An important advantage of the balloon technique over most methods employing aircraft lies in the fact that the balloon and its cables can be kept entirely non-metallic. The absence of nearby reflecting surfaces preserves the cylindrically symmetrical free-space radiation pattern of the balloon-borne dipole, thereby eliminating a troublesome correction factor which would otherwise be involved.

2. GENERAL REQUIREMENTS.

In general, measurements of the spatial distribution of the far-field (true radiation pattern) of an antenna system must be undertaken with a test device which is effectively outside the induction field (or near-field) of the antenna. At a distance of 16 wavelengths from a current element the induction field is down to 1% of the radiation field: a negligible contribution for most practical measurements.

Furthermore, all measurements of the far-field must be carried out at a sufficient distance from the antenna system to ensure that the true free-space radiation pattern is approached. To meet this requirement the incident wave from an external source antenna must be nearly uniform in amplitude and phase across the effective aperture of the antenna system under test. The variations which can be tolerated across the width of the aperture are commonly taken to be $\pi/8$ radians in phase and 1/4 db in amplitude (Cumming, 1959).

If d is the effective subtended aperture of the antenna under test and r is the distance to the external source antenna as shown in Figure 1, then

$$\Delta r = \frac{d^2}{8r} \quad \text{neglecting terms in } \Delta r^2.$$

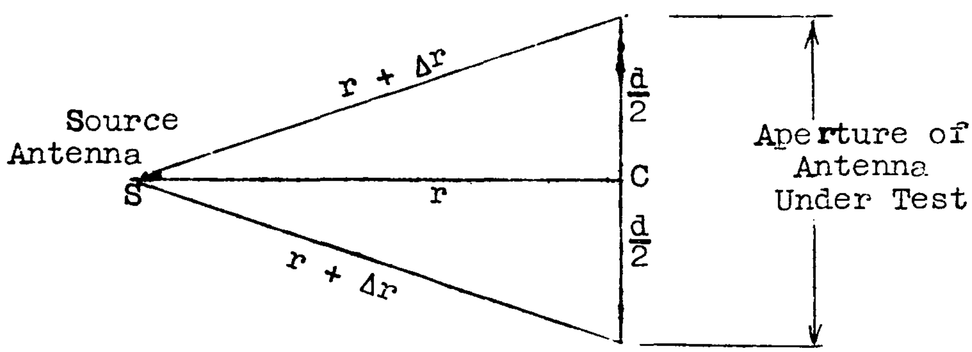

FIGURE 1. Diagram for calculating the variation in phase across the aperture of an antenna.

The effective subtended aperture d refers to the antenna dimension perpendicular to the distance r, and as the position of the source antenna is changed during a series of measurements so the value of d is liable to change.

The condition that the phase difference between the incident wave at the edge of the array and that at the centre be not greater than $\pi/8$ radian is given by

$$\frac{2\pi}{\lambda} \Delta r \leqslant \frac{\pi}{8}$$

Eliminating Δr from the previous equation gives the condition

$$r \geqslant \frac{2d^2}{\lambda}$$

which must be satisfied for all positions of the source antenna.

Nevertheless this condition may be relaxed whenever measurements are made at fixed radius in a plane containing the centre of the antenna array under test. The minimum radius given by the above equation is obtained by taking for the aperture width d the maximum dimension of the array in the plane of measurement, even if the array length is considerably greater normal to the plane of measurement. The results will be quite valid provided the phase <u>differences</u> between the various contributions from along the length of the array remain constant within the above limits for all positions of the source antenna. When dealing with extensive arrays this property of fixed-radius measurement techniques can be very advantageous.

3. THE BALLOON TECHNIQUE.

Consider a balloon-borne transmitter B tethered at two points F and G equidistant horizontally from the centre C of an antenna under test, as shown in Figure 2. Measurements of the radiation pattern of the antenna are

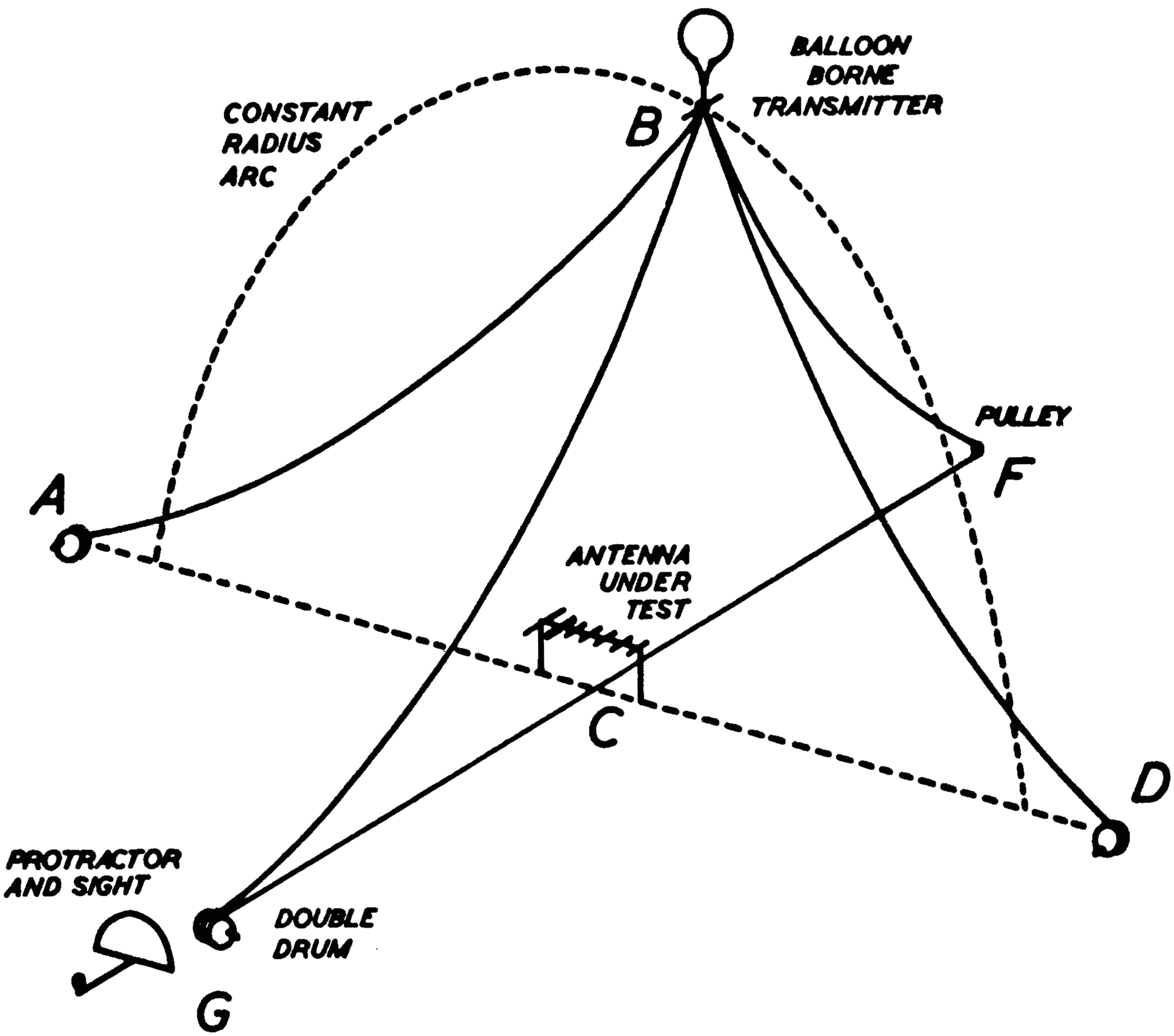

FIGURE 2. PHYSICAL LAYOUT OF THE CABLES AND SIGHTING APPARATUS FOR CONTROLLING THE BALLOON AND MEASURING ITS POSITION.

to be made in the plane containing B and C normal to the line joining F and G. The tethering cables BF and BG, provided they are fairly light, constrain the balloon to a constant radius arc within the measurement plane as the lengths of the traversing cables BA and BD are altered. This is not at all difficult to achieve provided A and D are located several yards outside the arc of constant radius and the traversing cables BA and BD are not pulled so tightly that the tethering cables BG and BF slacken.

If a light wind is blowing the balloon is kept within the plane of measurement by a small differential adjustment of the tethering cables. These cables, BF via a pulley at F, and BG, are returned to opposite sides of a double winding drum at G to enable a single operator to wind one cable in as the other is wound out. This adjustment has the effect of altering the cable tensions (to cope with the wind force) by varying the relative amounts of sag in BG and BF. For full effectiveness in this respect the distance FG should be approximately 2 to $2\frac{1}{2}$ times the arc radius. It should also be mentioned that the tethering cables BG and BF are attached one at each end of the balloon-borne transmitter in order to provide a restoring couple for keeping the transmitting dipole in correct alignment.

The winding-drum operators at A and D alter the length of the traverse cables under instructions from a controller at G who monitors the balloon's position with the aid of a protractor and cross-wire sight. Using a large transparent protractor the angle BCD may be obtained to well within one degree, and if concentric circles are engraved on the protractor the radius of the arc followed by the balloon may also be checked, and adjustments or allowances made accordingly.

The signal level from a receiver connected to the antenna should be displayed near the controller at G who can then record signal strength as a function of balloon elevation. The receiver should have a dynamic range of the order of 60 db if best results are to be obtained with high gain antennas. A receiver with logarithmic response is ideal but a conventional type of receiver with linear response is perfectly satisfactory provided that it is well shielded and a calibrated attenuator is available to insert in the input for extending the receiver's dynamic range without risk of overload.

The balloon-borne transmitter should be kept as simple as possible consistent with good stability. A circuit employing a single transistor delivering 10 milliwatts of R.F. power output will be ample for almost any antenna measurement using this technique. The battery capacity must, of course, be adequate to sustain a constant power output throughout the measurements.

4. DATA ON BALLOONS AND CABLES.

Balloons capable of lifting up to 57 kg when filled with hydrogen are readily available as they are used constantly in meteorological work. The sizes of typical balloons and their lifting capacities are given in Table 1.

TABLE 1. BALLOON SIZES

Empty weight (grams)	Inflated Volume (metres^3)	Inflated Volume (feet^3)	Payload Capacity (kg)	Payload Capacity (lbs)
650	3.2	115	2.6	5.7
800	4.3	150	3.5	7.7
1000	5.8	205	4.7	10.4
1750	12.0	425	10.4	23.0
2400	18.7	660	16.5	36.4
7000	63.7	2250	57	126

The inflated volumes in Table 1 are those given in the manufacturer's data and should be taken as a guide rather than an exact measure of the hydrogen required. For example, it was found that 800 gm balloons usually took the entire contents of two 100 cu. ft. cylinders of hydrogen gas without showing any signs of weakening. Over-inflation was, however, only resorted to when necessary to combat the effects of light breezes.

The precautions which must be taken when handling hydrogen gas in the open air are simple enough. Ignition by static discharge must be prevented by earthing the balloon via a filling hose made of conductive rubber.

Thin nylon line is by far the best material for the tethering and traversing cables. It is light yet strong and does not absorb moisture. Its low surface friction enables it to slide over the ground and snag less readily than string or twine, but does make extra care necessary whenever knots need to be tied.

A wide range of nylon line sizes is usually available from sporting goods suppliers. Samples were obtained and tested in order to ascertain which size would be the best. The results are shown in Figure 3. The values of breaking force were obtained by an Avery type 7106 CCG Tensile Testing Machine which applied strain at the rate of 21 inches per minute.

For the larger gauges of nylon line the breaking force quoted by the maker was found to be conservative, as shown by the arrows in Figure 3 which fall below the test values indicated by the crosses. On the other hand for thinner gauges of line there was an increased likelihood of failure under loads less than those quoted by the maker. The thin gauges of nylon line were noticeably weakened by small surface nicks; these caused the line

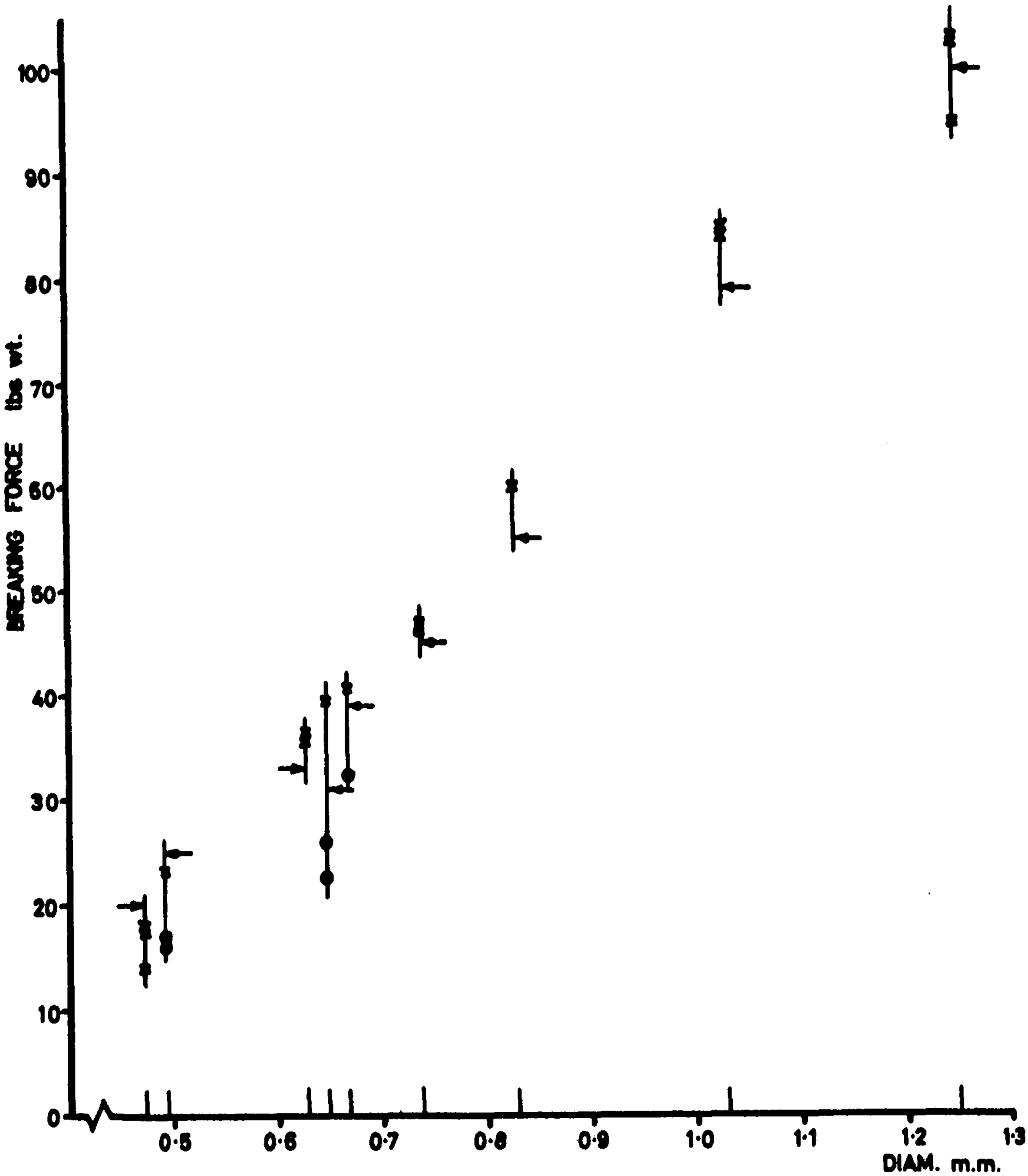

FIGURE 3. BREAKING FORCE AS A FUNCTION OF DIAMETER FOR VARIOUS SAMPLES OF NYLON LINE. ARROWS INDICATE MANUFACTURER'S DESCRIPTION, E.G. "20-POUND LINE". CROSSES SHOW BREAKING FORCE WHEN THE LINE FAILED BEFORE SNAPPING. CIRCLES SHOW BREAKING FORCE WHEN A SHARP SNAP OCCURRED, PROBABLY DUE TO SLIGHT NICKS ON THE SURFACE OF THE NYLON.

to fail with a distinct "crack" (at loads indicated by the circles) instead of drawing to a neck and parting.

The 45-pound nylon line was found to be very suitable for use with 800 or 1000 gm balloons. 3000 feet of this line weighs only half a kilogram (density of nylon is about 1.14 $gm.cm^{-3}$) and is sufficient to allow, from the geometry of Figure 2, an arc radius of 500 feet. This leaves ample lift for a transmitter and dipole, and for providing the tension in the cables necessary for good horizontal control of the balloon.

5. RESULTS.

The majority of the measurements using this technique were made at frequencies near 69 Mc. on a variety of antenna systems. A typical result is shown in Figure 4, which represents the vertical radiation pattern of an array of twelve horizontal half-wave dipoles spaced one eighth wavelength in front of a wire net reflecting screen. The configuration of the dipoles is shown in Figure 5.

It is apparent from Figure 4 that the actual radiation pattern follows the calculated pattern very closely, with most of the radiated energy being sent in the intended direction. A small amount of energy is lost to the rear due to an imperfect reflector screen and the fact

A. *CALCULATED*

B. *MEASURED*

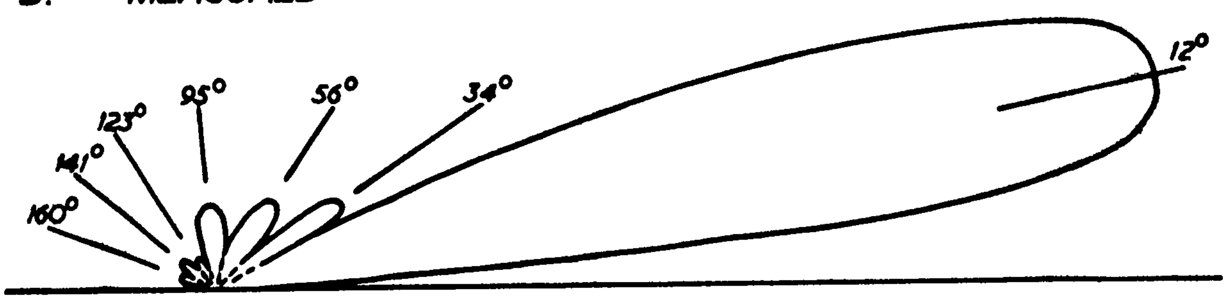

FIGURE 4. *Vertical Radiation Pattern of a 4 x 3 Array at 69 Mc/s.*

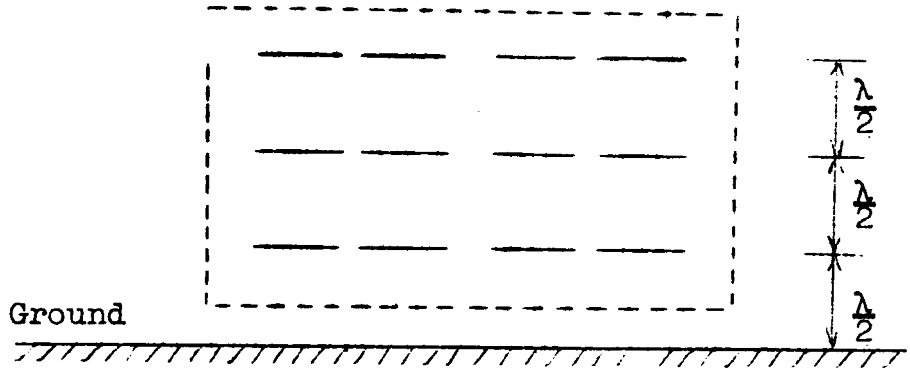

FIGURE 5. Configuration of the 69 Mc. 4 x 3 dipole array.

that it did not extend high enough to be fully effective for the uppermost row of dipoles. The high elevation lobes of the pattern are shifted somewhat as a consequence of this.

Figure 4 (b) is the average of the results from two complete traverses of the array by the balloon; one in each direction. The difference of one degree between the calculated and measured values of elevation of the main lobe might be due to experimental errors although it could have arisen from a faulty design assumption concerning the depth below the surface of the ground at which reflection occurs. However, it is obvious from Figure 4 that this particular antenna is performing very close to expectations.

6. CONCLUSIONS.

It is not difficult, using this balloon technique, to obtain results which have an overall accuracy of better than 10%. This figure depends mainly on the signal strength calibration accuracy of the receiver and attenuator, as well as on the ability of the field personnel to keep the balloon close to the required flight-path. In this respect it is worth mentioning that even the poorest of the balloon flights yielded results which were better than those obtained when a helicopter was employed for making the same measurements.

Furthermore the balloon technique is very inexpensive in terms of manpower and equipment when compared with other techniques. Under favourable weather conditions it is normal for a team of four to measure both the vertical and horizontal radiation patterns of an antenna system in well within half a day. This assumes that the necessary apparatus is properly prepared and the positions A, D, F and G (Figure 1) have been surveyed and pegged out beforehand.

The range of frequencies at which it is profitable to use a balloon technique extends from roughly 20 Mc. to 500 Mc. Below 20 Mc. the necessary arc radius exceeds 800 feet, which is about the limit for satisfactory control over a tethered balloon. Above 500 Mc. the arc radius becomes small enough to permit the use of rigid booms for supporting the source transmitter and dipole.

7. ACKNOWLEDGMENTS.

The authors wish to thank the New Zealand Meteorological Service for their valuable advice on the handling of hydrogen-filled balloons, and for the gift of several balloons. The co-operation of Mr. F. W. Fahy of the School of Engineering, University of Canterbury, in the testing of the samples of nylon line is much appreciated.

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